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Efficient and Reliable Reactive Power Supply and Consumption – Insights from an Integrated Program of Engineering and Economic Research

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Efficient and Reliable Reactive Power Supply and Consumption – Insights from an Integrated Program of Engineering and Economic Research

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In 2005, the Federal Energy Regulatory Commission (FERC) began discussing regulatory policy for reactive-power procurement and pricing in competitive electricity markets. This paper summarizes findings from a unique, interdisciplinary program of public-interest research that lays a formal foundation for evaluating aspects of FERC staff recommendations and offers early insights that should be useful in guiding policy implementation, specifically by:

- clarifying the consumers and economic characteristics of reactive power as a basis for creating incentives to appropriately price it,
- defining specific challenges in creating a competitive market for reactive power as well as new tools needed to help ensure such a market functions efficiently, and
- demonstrating the importance of accounting for the physical characteristics of the transmission network in planning for reactive power and avoiding the exercise of market power by suppliers.

1. The FERC Staff Report

FERC's 2005 staff report "Principles for Efficient and Reliable Reactive Power Supply and Consumption"ⁱ is a thoughtful discussion of reactive power's essential role in enabling the reliable delivery of real power and of the many issues that must be addressed in economically procuring reactive power. The staff report is significant because it expresses economic regulators' formal recognition of the need to explicitly account for the physics of the electricity delivery system in establishing appropriate economic incentives for suppliers and consumers of reactive and real power.

The FERC staff report identifies six concerns related to reactive-power supply and consumption:

1. Discriminatory compensation,
2. Rigid but imprecise interconnection standards that are insensitive to local needs,
3. Lack of transparency and consistency in planning and procurement,
4. Poor financial incentives to provide or consume reactive power,
5. Poor incentives for some system operators to procure reactive power and reactive-power capability at least cost, and
6. Failure of system operators to adjust reactive-power instructions to fully optimize dispatch.

The report makes four broad recommendations to address these problems and concerns:

1. Reactive-power reliability needs should be assessed locally, based on clear national standards.

2. Reactive power should be procured in an efficient and reliable manner.
3. Those who benefit from reactive power should be charged for it.
4. All providers of reactive power should be paid, and on a nondiscriminatory basis.

The report articulates two important goals for a well-designed pricing mechanism: “The first is to encourage efficient and reliable investment in infrastructure needed to produce reactive power and maintain the reliability of the transmission system. The second is to encourage efficient production and consumption of reactive power from the existing infrastructure, taking into account the opportunity costs of competing uses of resources, so as to keep rates low.”

The report concludes that “the ultimate goal should be an integrated set of co-optimized markets with bilateral markets relatively free from federal regulation.” This conclusion is followed by a long list of questions that FERC staff plan to address, with the recognition that “this goal requires research, software development, education and testing, and is likely to require 5 to 10 years to fully implement.”

2. An Integrated Program of Engineering and Economic Research on Restructured Electricity Markets

With support from the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability and the National Science Foundation, we have been researching and developing a comprehensive set of integrated market/engineering design principles and tools for a restructured electricity industry.ⁱⁱ Our program is unique because it emphasizes equally the effects of the physical electricity network on electricity markets and the effects of the market on the physical network.

Our research objective is pursued through an interdisciplinary program that includes:

- *Theoretical analysis* – conducting conceptual abstract modeling and analysis employing techniques of operations research, systems analysis, micro economics, stochastic modeling, game theory, and auction theory;
- *Empirical analysis* – gathering and interpreting empirical data and estimating and validating theoretical models using econometric methods, financial engineering approaches, statistical analysis, and data mining;
- *Computational methods* – using numerical methods and agent-based models to simulate and forecast market outcomes with realistic modeling of the electric power system in conjunction with behavioral models of economic agents that control various aspects of the system and interact in the market place; and
- *Experimental economic approaches* – performing controlled laboratory experiments with live and artificial agents to explore decision patterns under alternative rules and system conditions and to test behavioral assumptions upon which such rules are founded.

Most recently, work has focused on:ⁱⁱⁱ

- The theory, design and testing of multi-dimensional markets, taking into account special problems of coordinating and planning for efficient power transfer across

- control areas while preserving or enhancing reliability within control areas (seams issues);
- Developing and testing market mechanisms for providing static and dynamic reactive power;
- Developing enhanced market reliability metrics that can be implemented for real-time market monitoring and off-line analysis; and
- Introducing a time dimension into tests and analyses of market performance to evaluate long-run decisions (e.g., investment in generation and transmission).

This paper summarizes selected findings from our work that offer perspectives on and insights into the four broad recommendations and supporting questions raised in the FERC staff report.^{iv} We comment on:

- The analytical basis for establishing competitive markets for reactive power;
- The rationale for organizing this market as a contingent-claim market;
- The need for better tools to calculate real-time prices for reactive power; and
- The challenges involved in identifying and addressing market power in real and reactive-power markets.

3. Establishing Reliability Requirements for Reactive Power

It is generally accepted that the reliability of the electricity supply in an area is a public good because each customer served from the same feeder or network experiences the same unplanned outages. As a public good, reliability will be under-provided at the levels desired by society at large if it is provided solely by parties acting individually in their own self-interest. This characteristic is acknowledged implicitly in the FERC staff report's first recommendation: "Reactive power reliability needs should be assessed locally, based on clear national standards."

Our recent work has been to analyze the claim that reliability is a public good.^v We have isolated the aspects of reliable electricity delivery that can feasibly be provided through market mechanisms and distinguish them from other aspects that cannot be provided completely by these mechanisms.

To summarize, we find that both real and reactive power are technically private goods because they are "excludable" and "rival." "Excludable" means that consumers can be kept from enjoying a good either by sellers or by a consumer who owns a good that an individual consumer chooses whether to buy as well as how much of it to buy. "Rival" means that a good that is consumed by one person cannot be consumed by another. We find that voltage, system frequency, and operating reliability (e.g., operating transmission lines to meet N-1 criteria) are public goods. Public goods are not excludable and not rival.

A simple example of a private good is an apple. If you buy one, no one else can take that apple away from you (legally anyway), so it is an excludable good. Similarly, if you eat (consume) it, it is gone, and no one else can enjoy eating it, so it is a rival good. As a

result of these characteristics, private firms can produce and have appropriate incentives to supply private goods to customers.

In contrast, an example of a public good is a street sign placed on a residential corner, which can be seen by all who pass by. It is not excludable (or it would lose its purpose). Similarly, a driver of a passing car who needs information provided by the sign can obtain the information from it without diminishing the ability of a second driver to obtain information from the sign. Thus, the sign is not a rival good. These properties make provision of public goods by private firms difficult or impossible because firms cannot expect to get paid by each consuming individual if, once the service is provided, everyone can enjoy it without diminishing a neighbor's satisfaction.

The significance of finding that voltage is a public good is that private incentives alone will be insufficient to provide voltage consistent with the societal desire for reliability. A "central authority" will be required to ensure that this public good is provided adequately. That is, consistent with the FERC staff report's first recommendation, a central authority is required to establish appropriate standards for voltages (as well as for system frequency and operating reliability criteria). The "central authority" here is the North American Electric Reliability Corporation (NERC), recently certified by FERC to be the Electricity Reliability Organization (ERO) created under the Energy Policy Act (EPACT) of 2005.

Although these findings may not seem controversial or revolutionary, we believe that they can be very helpful in making future discussions of reactive power clearer and more precise. For example, on the basis of these findings, we can now distinguish between the public-good nature of the voltages we seek to maintain in our transmission system, which a market cannot establish, and the private-good nature of the reactive power we seek to acquire to maintain these voltages, which a market may be able to provide. The analogy with the street sign reveals that, although a central authority is required to establish the need for, location of, and shape and design of, for example, a stop sign (e.g., "according to clear national standards"), private firms can, in principle, effectively compete with one another to fabricate, erect, and maintain stop signs consistent with these requirements.

Our work also helps to clarify that, in fact, there are two consumers of reactive power in an electric power system. The first consumer is, as just mentioned, the system operator, who is responsible for acquiring adequate quantities of reactive power in the right locations to maintain voltages (i.e., requirements that are "assessed locally"). The second consumer is market participants (typically, firms) that must consume (and might provide) reactive power to keep their equipment running (a private good). As we will discuss below in Section 4.2, ensuring that reactive power is priced correctly is especially important in creating appropriate incentives for these market participants to consume or supply reactive power efficiently.

4. Desirable Characteristics of Efficient Markets for Reactive Power

FERC staff's second recommendation, that reactive power "should be procured in an efficient and reliable manner," requires that we consider how reactive power should be procured. The FERC staff report identifies four mechanisms for paying for reactive power, and, if capacity payments are used, four supporting approaches. The report acknowledges that "the idea of a bid-based reactive power spot market is new and we believe it is too soon to implement one. Simulation and experimentation are needed to understand the effects of alternative auction market designs."

Our research has identified two important challenges that must be addressed in creating efficient markets for reactive power.^{vi} The first challenge arises from the volatile yet relatively low reactive-power prices that would likely emerge most of the time from competitive real-time markets. Addressing this problem requires that we consider forming contingent-claim markets to ensure real-time availability of adequate supplies of reactive-power capacity. The second challenge arises from the continuing need to establish real-time prices for reactive power to ensure that market participants make efficient consumption decisions. Addressing these challenge requires that we begin to develop new software tools that determine these prices accurately.

4.1 The Rationale for Establishing Contingent-Claim Markets for Reactive Power

We find that nodal real-time prices for reactive power will almost always be zero when there has been optimal investment in reactive-power sources (i.e., both generators and static sources).^{vii} One way to think about this is that when the system is intact, the "static" reactive power needed for transmission is supplied mainly by capacitors/inductors because this type of equipment is relatively inexpensive to install. Another way to think about this is to imagine that most generators are operating within their capability (or "D") curve such that there is no incremental (i.e., no opportunity) cost associated with increasing reactive-power production.

Using simulations of optimal operation of and investment in reactive capacity, we find that non-zero real-time prices for reactive power will arise only during contingencies, such as when equipment fails. That is, there is a demand for "dynamic" reactive power (which is typically provided by generators) only when a contingency stresses the system. In this circumstance, one can imagine that generators might be operating at the real-power-production boundary of their capability curves, so there would be an opportunity cost, in the form of foregone real power production, associated with increasing reactive-power production.^{viii}

We also find that the average or expected revenue from sales of reactive power at optimal real-time prices, which are likely to be non-zero only during contingencies with adequate reactive capacity, is sufficient to provide incentives for optimal private investment in reactive-power capacity. This is an important finding. It means that once the level of reliability consistent with the public good is set, a competitive market is, in principle, capable of eliciting levels of investment in reactive-power capacity that are consistent with the public-good objective of maintaining reliability.

Nevertheless, as noted, the reactive-power revenue stream is highly volatile, uncertain, and dependent on contingencies. As a result of this volatility and uncertainty, private investments in reactive capacity will be inherently risky. However, we also find that when reactive capacity is in short supply, the willingness to pay or the social value of reactive power is many orders of magnitude greater than the incremental cost of investments to increase reactive-power supply. In other words, it is optimal to make large investments in reactive-power capacity to prevent shortages even though those shortages are rare occurrences.

When a market for a private commodity involves financial transactions that would take place only on rare occasions and when the market itself is expensive to operate, natural economic forces will restructure the market to avoid or minimize transaction costs.^{ix} The type of transaction that emerges naturally from such market conditions is called a contingent claim, which is a claim for services that can be made only if one or more specified events occur.

In a contingent-claim market for reactive power, the central authority would essentially rent major reactive-power sources from suppliers that submit the lowest-priced offers and then instruct these suppliers on how to operate those sources in real time. These markets would operate well in advance of the contingencies that justify the claims (i.e., the actual dispatch of reactive power) for two reasons. First, the central authority responsible for reliability and operations needs reactive power on demand so that it can deal with contingencies in real time and thereby assure reliability. Second, up-front investment is required to assure that all demand can be met.

Contingent-claim markets are appropriate for reactive power because they would close well in advance of any claims that would be made. If they are run sufficiently far in advance, they can provide a stable source of revenue and thereby encourage investment. Rather than obtaining revenue through unpredictable rare contingencies, sources that submit winning offers would obtain steady revenue in the form of rent, to compensate them for providing reactive power on demand.

Note that, because this market is run far in advance, the central authority must project the amount of reactive power needed to serve private buyers and to maintain voltage. Thus, based on the central authority's determination of how much reactive power will be needed and where (projected nodal demand), the market must be run locally to acquire reactive-power sources efficiently.

There is also another, potentially more compelling, reason for establishing a contingent-claim market for reactive power. Based on both simulations and economics experiments, we find that opportunities for the exercise of market power by private reactive-power suppliers in real-time markets are plentiful in a network environment in which transmission of reactive power is limited to short distances, as established by Kirchoff's laws. Thus, even with sufficient reactive-power capacity, suppliers are likely to submit offers that will produce positive real-time reactive-power prices in non-contingency states for which optimal prices are zero.

These conclusions are based on laboratory economics experiments conducted on two types of market arrangements using the network shown in Figure 1. Experimental economics is a powerful technique that uses human (and in some cases, artificial-agent) participants, to explore the performance of electricity markets under alternate designs and system conditions.

Figure 2 shows nodal reactive-power prices computed from a full alternating current optimal power flow (AC OPF) simulation over rounds for an experiment in which sellers of reactive power were paid a fixed price for their services, approximating a contingent-claim market. Note that, similar to what we saw in the optimal simulations described above, nodal prices are very low or zero most of the time in the first half of the experiment because reactive-power limits are reached only occasionally. In the second half of the experiment, reactive capacity is reduced far below desirable levels to show what might happen in a contingency.

In contrast, Figure 3 shows reactive-power prices over rounds in an experiment conducted with the same network and system conditions including load on each round represented in Figure 2. However, in this case a real-time market for reactive power is added, in which generators make offers into two separate auctions, one for reactive power and one for real power on each round. Nodal prices now show the effect of lack of competition resulting from network constraints on the flow of reactive power that allows generators to raise their offers in the real-time market.

Based on the results of experiments illustrated in Figures 2 and 3, it is very likely that market power will be a serious problem for the supply of reactive power in real-time markets, more so than for the supply of real power.

It should be noted that the overall demand for reactive power comes in great part from the central authority responsible for system operations and providing reliability to meet public needs. Competitive prices will be assured in contingent-claim auctions only if some offered units are potentially excluded. A contingent-claim auction for reactive power that is run sufficiently far in advance to allow construction to occur (one to five years depending on the source) would place existing suppliers in competition with potential investors and new sources of reactive power and thus encourage competitive prices. (We continue the discussion of market power in real and reactive-power markets in Section 5 below.)

4.2 The Need for New Tools to Establish Accurate Market Prices for Real and Reactive Power

The need for a contingent-claim market to elicit adequate supplies of reactive power does not eliminate the need to establish accurate real-time nodal prices for reactive power. As noted earlier, ensuring that reactive power is priced correctly is especially important to create appropriate incentives for market participants to consume reactive power efficiently. The need for nodal reactive-power prices is expressed in FERC's

recommendations that “those who benefit from the reactive power should be charged for it” and that “all providers of reactive power should be paid, and on a nondiscriminatory basis.”

As a result of our simulations and experiments of real- and reactive-power markets, we have identified an important, yet not widely acknowledged, shortcoming in the current software tools used by the industry to establish these prices. The shortcoming is that these tools are based on a “decoupled” formulation of the power-flow problem (known conventionally as a “DC power flow”). Although the DC formulation can account directly for thermal limits on transmission lines in its solution (and hence in nodal prices), it cannot account directly for voltage limits. Accounting for voltage limits is essential for establishing correct nodal prices for both real and reactive power. Consequently, the manner in which these limits are taken into account is an important topic that we believe has not been fully examined in the development of software tools to support the operation of competitive electricity markets.

Both our simulations and experiments are based on what is known as a full AC OPF. This formulation accounts directly for voltage limits. We find that optimal investment in transmission lines leads to a situation in which thermal line constraints are never binding, even during contingencies. As noted, we find that substantially different nodal prices for both real and reactive power arise only during contingencies. In contrast, a DC OPF tool would yield no such differences in nodal prices under these conditions.

This is not to say that voltage limits are not taken into account using DC power-flow tools. However, these limits are taken into account indirectly using so-called “proxy” methods. Proxy methods re-express voltage limits as line-flow limits, which can be accounted for in DC power-flow tools. The problem with this approach is that a voltage limit can be re-expressed in more than one way as a proxy limit on a line flow; there is no single, unique translation. Differences among the methods for re-expressing these limits can lead to differences in the resulting prices.^x Worse, these differences typically are greatest at the times when a voltage constraint is binding, which is precisely the time when accurate prices are most needed to provide the correct signal for efficient consumption and investment decisions.

As a practical matter, we note that the proxy methods are rarely, if ever, publicly documented. To our knowledge, the procedures in current use by regional transmission organizations (RTOs) to implement these limits have never been reviewed to assess the impact of alternative approaches on the prices that result. Two major topics of our current research are review of these approaches to better understand the different impacts they have on prices and development of new methods to implement full AC power-flow solutions on realistic-sized power systems.

In summary, nodal prices emerging from a DC power-flow simulation may yield incorrect price signals for consumption and production of reactive power in the short term and investment in reactive-power capability in the long term. Proper incentives require that investment decisions be based on accurate nodal prices for real and reactive

power. Demonstrably correct prices can, at this time, only be derived from a full AC power-flow simulation. Large customers and marketers should pay real-time nodal prices for real and reactive power. Marketers will then have incentives to install metering and either pass on real-time prices or install automated controls on customer equipment in exchange for a lower fixed rate.

As noted, we do not believe that a real-time spot market is appropriate for reactive power because of the opportunity for suppliers to exercise market power. Rather we propose that the independent system operator (ISO) procure supplies of reactive power in a contingent-claim market conducted well in advance. These sources would ideally be dispatched by the ISO using a full AC power-flow simulation that calculates nodal reactive-power prices. Consumers of reactive power should be charged these nodal reactive-power prices to enable economically efficient development of distributed energy resources and load response.^{xi} The annualized value of additional reactive power at each node can then be computed from real-time nodal prices and used by the ISO to construct the appropriate demand curve for obtaining reactive power in the contingent-claim market.

5. The Need to Account for the Electrical Characteristics of the Transmission Network in Addressing the Problem of Market Power

A major focus of our research has been market power in wholesale electricity markets. An important strength of our interdisciplinary approach is that we can directly explore the implications of the adage, “VARs don’t travel.” Our work has allowed us to identify a variety of ways by which the ever-changing configuration and utilization of transmission networks can confer market power on participants in both real- and reactive-power markets. The work has also been humbling in reminding us that, although these opportunities are typically very subtle, exploiting them does not require that market participants be experts in Kirchoff’s equations. Our combined findings point to a major limitation of current static market-power tests or screens: the difficulty in applying them meaningfully to markets in real time. As a result of this concern, we are developing and testing approaches to detect market-power opportunities in real time based on explicit consideration of the real-time status of the transmission network.

5.1 Reactive-Power Requirements Interact with Real-Power Markets in Unexpected Ways

We conducted a number of experimental economics tests to identify how production of reactive power by generators interacts with the market for real power.^{xii} We have documented three distinct examples of increasing complexity.^{xiii}

First, we conducted experiments in which participants representing individual generators “learn” that they are in a load pocket, which has been created as a result of voltage limits during high-load periods. The important implication for market power is that the participants did not know that system conditions and network topology had evolved to create a situation in which their generators were effectively “reliability must run” (RMR)

units. They simply learned, through trial-and-error submission of offers for real power, that, during high load periods, they could offer the initial block of real power from their generators at the price cap and always be accepted.

Second, we examined unit-commitment algorithms and observed unexpected patterns of optimal dispatch that challenge traditional beliefs about standard unit-commitment procedures. In these experiments, participants controlled a portfolio of units, including base-load, cycling, and peaking. Normally, peaking units would rarely be dispatched at night. However, because cycling units were shut down at night (as a result of the unit-commitment process), the operator's flexibility to dispatch reactive power at night was greatly reduced. In this situation, peaking units were dispatched against their lower operating limits because their real power is expensive, but their reactive capability was used. If this network were used in a market, the peaking units would have exactly the same type of market power discussed in the first example.

Third, we have found that, for certain topological configurations, the ability to set higher prices in the load pocket can "cascade" upstream along the paths of the congested transmission lines serving the load pocket. Other generators may be able to unilaterally raise their prices (and profits) thanks to this cascading effect. In a competitive market that uses the last (most expensive) accepted offer to set the clearing price, the price setter can raise the clearing price only as high as the price of the first rejected offer, and the competition between the first rejected and the last accepted offers promotes honest marginal-cost offers. However, when there is congestion and there are only a few generators inside a load pocket, those generators have market power and can raise the clearing price by tacit collusion on the portion of the load inside the pocket that cannot be served by sources outside the pocket.

These examples of network conditions illustrate the complex characteristics of providing reactive power on a network and the surprising effects these characteristics can have on nodal prices for real power and the optimum commitment of units to meet load. The highly localized nature of the demand for reactive power means that suppliers of reactive power are likely to have market power in the type of auction typically used for real power. Thus, two problems related to market power should be investigated before the type of real-time market proposed by FERC is implemented: 1) The potential effects of market power in a VAR market on nodal VAR prices, and 2) The indirect effects of market power in a VAR market on the suppliers' level of market power in the companion real power market.

5.2 The Need to Account for the Transmission Network Explicitly in Assessing Market Power

The insights from our research collectively point to the importance, when assessing market power, of understanding the impact of both system conditions and the current state of the transmission network. However, current market-power monitoring techniques can only examine these impacts in an ad hoc fashion through either review of offer trends or highly aggregated measures of residual suppliers' capacities.

We recently initiated a program of research that may expand market-power monitoring opportunities by combining an alternative definition of market power with explicit consideration of the transmission network.^{xiv} First, it is important to understand that common definitions for market power rely on a comparison between market prices and so-called competitive prices and are therefore difficult to use in practice because the competitive price is not known when the market is not competitive and cannot be computed from data naturally available to the market. Our technique addresses this problem by not comparing prices but instead by identifying market participants (including clusters of market participants who might collude knowingly or unknowingly) that have the ability to increase their revenues by unilaterally increasing the price of their offers. This ability does not exist in competitive markets. We have also developed practical measures that quantify the extent to which market power, defined in this fashion, is being or could be exercised. The measures can be computed from data available to the system operator, including a solved state estimation model of the current power system and current set of offers. To date, we have proven these concepts with test systems. We are currently working with a well-known U.S. RTO to apply these methods retrospectively to a very large power system.

6. Conclusions

Past experiences with incompletely understood market designs have led to disastrous economic and political consequences. Rigorous application of well-tested engineering design principles is essential to avoid future disasters.

FERC's recognition of the importance of reactive power to reliable operation of power systems is a major step toward aligning regulatory economic policies with the actual physical properties and characteristics of electric power systems. Much work remains to be done, however, and science-based, public-interest research should continue to make contributions toward this end.

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End Notes

ⁱ Federal Energy Regulatory Commission (FERC). 2005. *Principles for Efficient and Reliable Reactive Power Supply and Consumption*. Staff Report. Docket No. AD05-1-000. Washington, D.C. February 4.

ⁱⁱ The DOE research program is coordinated by the Consortium for Electric Reliability Technology Solutions (CERTS). The founding members of CERTS include four national laboratories (Lawrence Berkeley, Oak Ridge, Pacific Northwest, and Sandia), the Power Systems Engineering Research Center (PSERC) consisting of 13 major universities, and the Electric Power Group. [<http://certs.lbl.gov>]

ⁱⁱⁱ See <http://certs.lbl.gov/reliabilityandmarkets>.

^{iv} The findings in this article are described in greater detail in R. Thomas, T. Mount, R. Schuler, W. Schultze, R. Zimmerman, D. Shawhan, and D. Toomey. 2006. *Markets for Reactive Power and Reliability: A White Paper*. Cornell University. December 5. Available at: <http://www.pserc.org/ecow/get/publicatio/2006public/>

^v See Toomey, D., W. Schulze, R. Schuler, R. Thomas, and J. Thorp. 2005. "Reliability, Electric Power, and Public Versus Private Goods: A New Look at the Role of Markets." *Proceedings of the 38th Hawaii International Conference on System Sciences*. IEEE.

^{vi} Op cit.

^{vii} See Timothy Mount, Steen Videback, and Ray Zimmerman. 2006. "Testing Alternative Market Designs for Energy and VARs in a Deregulated Electricity Market." *Proceedings of the 25th Annual Eastern Conference, Advanced Workshop in Regulation and Competition, Ruthers Center for Research in Regulated Industries*. Skytop PA. May 17-18.

^{viii} However, in contrast, we also find real-power prices exhibit much greater upside volatility than reactive-power prices. The reason can be traced to the high costs of investment in generation. These costs are so high that it is not optimal to invest in enough redundant capacity to cover all contingencies. We do find support for the conventional wisdom that it is appropriate (optimal) to invest in enough redundancy to cover the worst single contingency (e.g., loss of the "largest" generator). However, once this capacity is exceeded, peak prices are set by the value of lost load (i.e., customer's willingness to pay) because it is not optimal, from a societal standpoint, to invest in enough redundancy to cover the loss of multiple generators.

^{ix} Note that the rationale offered here for the formation of a contingent-claim market to secure adequate reactive-power capability is distinct from the traditional arguments offered to support capacity payments to deal with the "missing money" problem in real power markets, which arises in part both out of market actions by system operators and, especially, price caps on real power offers allowed in the market.

^x F. Alvarado. 2003. "Converting System Limits to Market Signals." *IEEE Transactions on Power Systems*, Vol. 18, No. 2, May.

^{xi} J. Kueck, B. Kirby, T. Rizy, F. Li, and N. Fall. 2006. "Reactive Power from Distributed Energy." *The Electricity Journal*. Vol. 19, Issue 10, December.

^{xii} For a discussion of this research approach, see, for example, Kiesling, L. 2005. "Using Economic Experiments to Test Electricity Policy." *The Electricity Journal*, Vol. 18. Issue No. 9. November. See also Zimmerman, R., R. Thomas, D. Gan, C. Murillo-Sanchez. 1999. "A Web-Based Platform for Experimental Investigation of Electric Power Auctions." *Decision Support Systems*, vol. 24, no. 3&4, January, pp. 193-205

^{xiii} Murillo-Sanchez, Ede, Mount, Thomas, Zimmerman. 2001. "An Engineering Approach to Monitoring Market Power in Restructured Markets for Electricity." *Proceedings of 24th IAEE International Conference*. Houston, TX, USA, April 25-27.

Murillo-Sanchez, C., R. Zimmerman, R.J. Thomas. 2001. "Kirchhoff vs. Competitive Electricity Markets: A Few Examples." *IEEE Power Engineering Society Winter Meeting*. IEEE, Volume 3, pp. 1256-1261.

^{xiv} See for example B. Lesieutre, R. Thomas, and T. Mount. 2005. "Identification of Load Pockets and Market Power in Electric Power Systems." *Decision Support Systems* 40 (2005) 517-528. See also H. Oh and R.J. Thomas. 2007. "Real and Reactive Power Prices and Market Power." *Proceedings of the 2007 PES General Meeting*. Tampa, Florida. June 24-28.

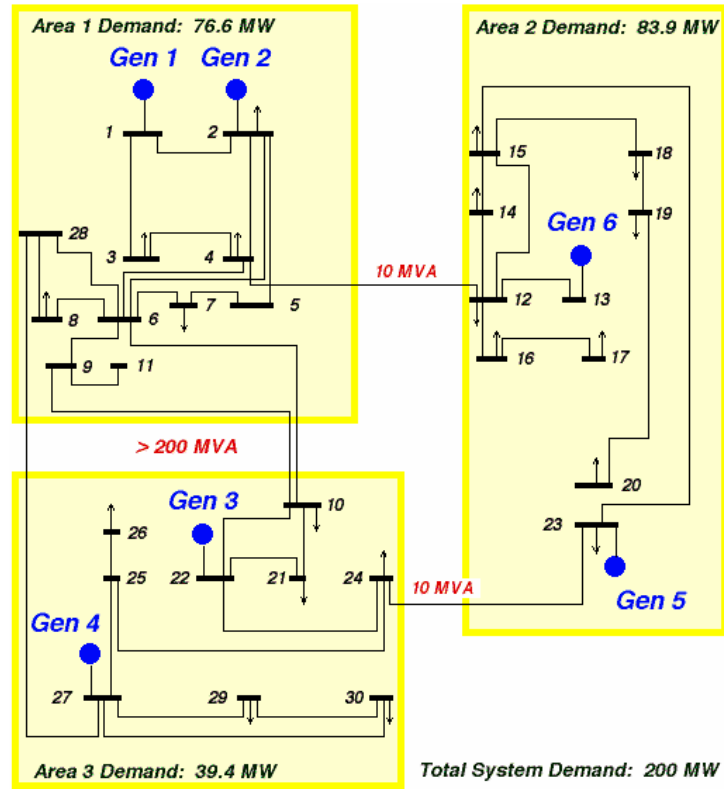
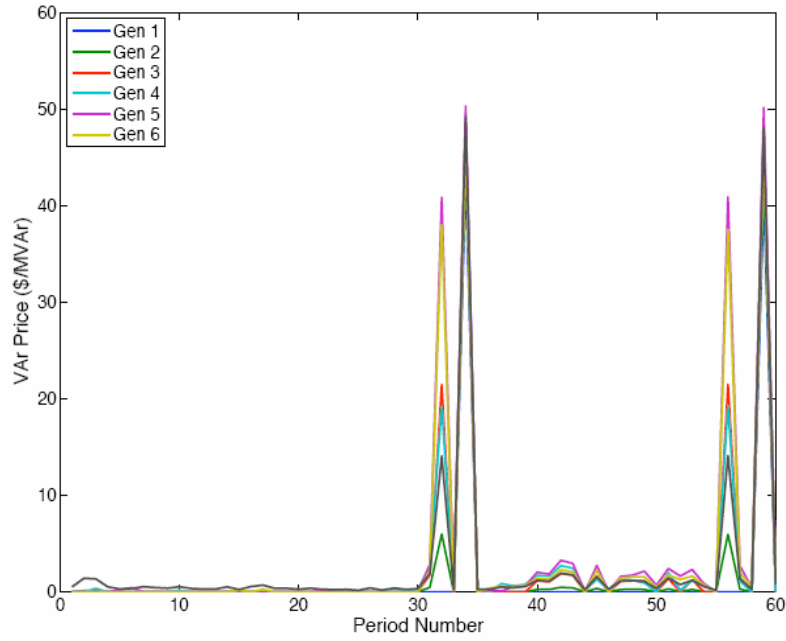
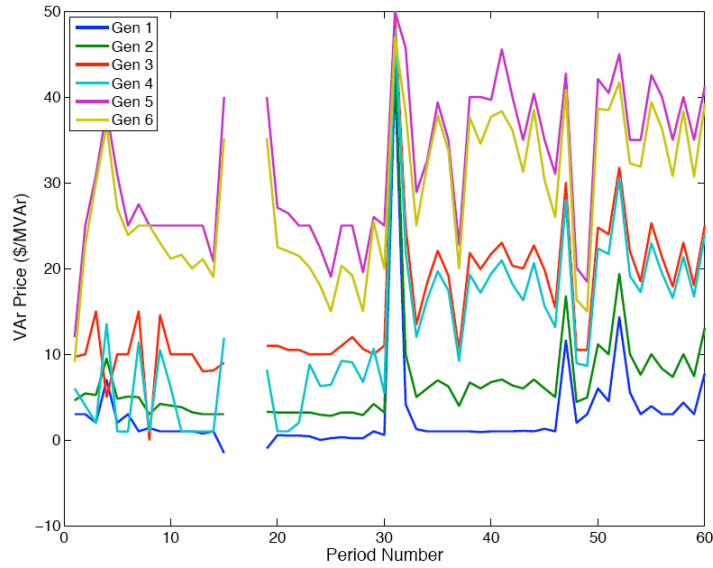


Figure 1: Network Used for Experiments and Simulations



Periods 1–30: Normal Capability Curves
Periods 31–60: Restricted Capability Curves

Figure 2. Nodal VAR Prices for Six Generators in Test 1



Periods 1–30: Normal Capability Curves
Periods 31–60: Restricted Capability Curves
(Gaps in the sequence correspond to trading periods in which the software did not find a solution.)

Figure 3. Nodal VAR Prices for Six Generators in Test 2